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In order to address the need for low-energy electronics design for mobile platforms in future Army communication systems a multidisciplinary effort is needed to investigate system and component design, simulation and optimization techniques. The emphasis in this research project is on the optimization, from a systems perspective, of energy requirements for a given performance level incorporating realistic models of device and circuit characteristics and energy consumption. The objectives of our project are to carry out detailed investigations to determine the best possible approaches and design methodologies to achieve significant energy reduction in a mobile platform performing various functions including communications, surveillance, detection, diagnostics and GPS direction finding.

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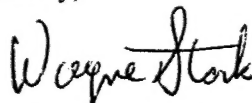
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# **Low Energy Electronics Design For Mobile Platforms**

**Final Report for Grant DAAH04-96-1-0377  
For the period September 1, 1996 to August 31, 2002**

## **Principal Investigators**

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Kamal Sarabandi	Robert Smith	Wayne Stark
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**Submitted December 3, 2002 to  
the US Army Research Office**

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## Executive Summary

In order to address the need for low-energy electronics design for mobile platforms in future Army communication systems a multidisciplinary effort is underway to investigate system and component design, simulation and optimization techniques. The emphasis in this project is on the optimization, from a systems perspective, of energy requirements for a given performance level incorporating realistic models of device and circuit characteristics and energy consumption. The objectives of our program are to carry out detailed investigations to determine the best possible approaches and design methodologies to achieve significant energy reduction in a mobile platform performing various functions including communications, surveillance, detection, diagnostics, and GPS direction finding.

In order to systematically attack the problem of minimum energy consumption electronic design of mobile platforms from a systems perspective we have defined four design layers. The four layers are: the distributed system layer, the local integration layer, the processing layer, and the device layer.

At the *distributed system layer* we have developed a methodology for simulation environment used to studying tradeoffs between the frequency of communication of position data and the position estimation accuracy in a situation awareness scenario involving a set of mobile platforms that includes energy consumption of the mobiles. We have studied the problems of supervisory control and diagnostics for systems with decentralized information. Our results lead to control and diagnostics strategies that are energy efficient in the sense that they minimize the amount of communication between the mobile nodes. We have developed energy and spectrally efficient media access control protocols for ad hoc wireless networks. The high performance attained by these protocols derives from exploiting the channel memory induced by shadowing, and appropriately combining corrupted packets with retransmitted packets. We have also investigated the relationship between deadlock-free information structures and concurrency. Such a relationship allows us to characterize the speed of response of mobile networks to various events, and provides guidelines on how to organize the information of mobile networks for routing purposes.

At the *local integration layer* we have developed a computationally efficient algorithm for selecting the energy-optimal configuration of sensors that achieves desired diagnosability properties. We have also developed a new technique for implementing the control logic that significantly reduces memory requirements at the price of a small amount of on-line computations.

At the *processing layer* we have investigated different signal and information processing algorithms used in a mobile platform for their energy efficiencies and system performance. For an equalizer we have determined the fundamental tradeoff between the performance (mean squared error) and power consumption of digital circuitry as the number of quantization levels in the received signal and tap coefficients vary. For a turbo decoder we have determined the tradeoff between performance (bit error probability) and power consumption as the number of quantization levels in a turbo decoder vary and as the number of iterations change. We have also investigated performance in various hostile environments such as multipath fading and partial-band interference. In addition we have developed algorithms for code combining with turbo codes and have analyzed the performance in a spread-spectrum systems. For a joint source and channel code we have determined the tradeoff in performance and power consumption as the number of computations assigned to the source code and channel code vary. Finally, we have found new error control codes that are better than all previously known codes for short packet sizes in terms of performance (minimum Euclidean distance) versus signal-to-noise ratio.

At the *device layer* we have developed models for high efficiency planar antennas and methods to analyze the efficiency useful in optimizing overall system performance. We have developed numerical techniques to determine propagation of radio waves that will be used in performance evaluation of communication systems. We have developed experimental techniques to measure nonlinear device performance for a power amplifier used in a communication system and have developed numerically efficient techniques to simulation nonlinear circuits. Finally, we have been developing methodologies to reduce power consumption in digital circuits using spectral techniques and low power quantum CMOS circuitry.

Finally, in order to verify the design tradeoffs and their impact on the overall system, we have developed a methodology for a simulation-based optimization environment that incorporates various aspects of the communications part of a mobile platform. The optimization procedure that we have synthesized makes use of the structure in this complex system by decomposing the overall optimization tasks into

three layers (network, processing, and device) that are interfaced by passing of key variables and tables. This optimization procedure employs different types of optimization at the different layers. Overall a simulated annealing algorithm for global optimization is used and shown to be computationally tractable. Furthermore we have shown the resulting decomposition of the simulation is still globally optimal.

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## 2 Scientific Personnel and Honors/Awards/Degrees

### Senior Investigators

Jack East	Alfred Hero	Linda Katehi
Stéphane Lafortune	Pinaki Mazumder	David L. Neuhoff
Kamal Sarabandi	Robert L. Smith	Wayne E. Stark
Demosthenis Teneketzis	Kimberly Wasserman	

### Students

Pablo Aghemo	Noel Baisa	George Barrett
William Benard	Oliver Boivineau	Mark Casciato
Houshou Chen	Richard Cheung	Mike Chu
Rami Debouk	Anurag Dod	Robby Gupta
Lee Harley	Sangjin Hong	Tara Javidi
Joseph Kang	Hyang Soo Kim	Sungkill Jim
Cheng-Po Liang	Jontae Lim	Chris Lott
Jeremy Muldavin	Thomas Panagiotis	John Shumpert
Rajiv Vijayakumar	Vuk Borich	Craig Wilsen
Jian-Jun Xiong	Daniel Zahn	Ketan Patel
Chia-Ning Peng	Maresh Godavarti	

During the grant five senior investigators became IEEE Fellows (Alfred Hero, Stéphane Lafortune, Pinaki Mazumdar, Wayne Stark, Demos Teneketzis).

Ph.D. Candidate George Barrett received the Student Best Paper Contest for the 1999 IEEE Conference on Decision and Control. The paper is titled "On the Synthesis of Communicating Controllers with Decentralized Information Structures for Discrete-Event Systems."

Wayne Stark has served on the Army Strategic Planning Committee (1997). Linda Katehi and Wayne Stark served on the National Science Foundation/Dod Committee studying Foreign Technology in Wireless Communications (1999,2000) and received the 2002 IEEE Military Communications Conference Award for Technical Achievement recognizing long-term technical "Sustained Contributions to Military Communications". Al Hero served on a DARPA (2000) study pannel on multuser detection.



Faculty Names	Award	Date Awarded
Coffey, John		
East, Jack	EECS Research	1994
Hero, Alfred	IEEE Meritorious Service	1999
	IEEE Signal Processing Society Best Paper	1999
	IEEE Fellow	1998
	EECS Research	1996
	G.V.N. Lothrop Fellowship in Engineering	1983
	One U.S. Patent Pending	
Katehi, Linda	IEEE MTT-S 1st Prize Symposium Paper	1998
	IEEE MTT-S Judge's Award Symposium Paper	1998
	IMAPS Best Paper	1997
	IEEE Microwave Prize, MTT-S	1996
	IEEE Fellow	1995
	UM Faculty Recognition	1994
	EECS Research	1993
	URSI Young Scientist	1987
	NSF Young Investigator	1987
	IEEE A. Schelkunoff Award, AP-S	1985
	IEEE W.P. King Award, AP-S	1984
	Amelia Earhart Fellowship	1983
	One U.S. Patent	1998
	One U.S. Patent	1997
	Two U.S. Patents Pending	
Lafortune, Stéphane	IEEE Fellow	1999
	EECS Teaching	1998
	EECS Research	1995
	IEEE Control Systems Soc. Best Paper	1994
	NSF Presidential Young Investigator	1990
	NSF Engineering Research Initiation	1987
Mazumder, Pinaki	IEEE Fellow	1999
	EECS Research	1995
	Digital's Incentives for Excellence Award	
	DARPA Research Excellence Award	
	B.F. Goodrich National Collegiate Invention	
	NSF Research Initiation	
	Bell Northern Research Laboratory Faculty	
	Two U.S. Patents Under Review	

Faculty Names	Award	Date Awarded
Neuhoff, David	EECS Outstanding Achievement	1999
	IEEE Fellow	1994
	CoE Service	1992
	1938E Distinguished CoE Service	1978
	One U.S. Patent	1997
	Four U.S. Patents	1995
	One U.S. Patent	1994
Sarabandi, Kamal	German and American Council Disting. Lecturer	1999
	Co-author 2nd place IEEE AP-S Student Paper (with Mark Casciato)	1998 1998
	UM Henry Russel	1997
	EECS Teaching	1996
	Two U.S. Patents Under Review	1998
Stark, Wayne	IEEE Military Communications Conference Award for Technical Achievement recognizing Sustained Technical Achievement in Military Communications	2002
	EECS Research	1998
	IEEE Fellow	1998
	EECS Service	1993
	Co-author 2 of 7 most significant papers Spreadspectrum Comm. Res.	1986-88
	NSF Young Investigator	1985
	Two U.S. Patents	1998
	One U.S. Patent	1986
	Four U.S. Patents	1996
Tenekeztzis, Demos	CoE Teaching	1999
	EECS Service	1998
	EECS Teaching	1993
	Outstanding Instructor by MSA	1990
	Outstanding Instructor by MSA	1989
	Best Paper of Session at ACC	1987
	Co-author 2 of 7 most significant papers Spreadspectrum Comm. Res.	1986-88
Wasserman, Kimberly	NSF CAREER Award	1998
	Army Research Office Young Investigator	1996
	GTE Corp. Graduate Fellowship	1990

### 3 Accomplishments

- First to develop a methodology for integrating the performance of physical layer with the network layer in ad-hoc wireless networks that also uses models that depend on actual consumed energy.
- First to develop tradeoffs between received processing energy and code performance.
- First to show how memory can influence the performance of actual codes very close to capacity for finite block lengths.
- First methodology to minimize energy in wireless networks including effects of nonlinear amplifiers, efficiency of amplifiers, receiver processing power.
- First to develop algorithms for frequency-hopped radios that jointly and iteratively estimate the channel and the data. We showed that the performance improvement of these algorithms with turbo codes was on the order of 6dB is energy relative to conventional techniques with Reed-Solomon codes.
- First to derive optimal bit allocation strategies for reduced power mixed resolution adaptive filters (fixed point LMS) used in channel equalization, matched filtering, and spatial beamforming with smart antennas.
- Characterized performance and derived algorithms for optimal vector quantization under detection fidelity criteria.
- Established that all popular partial update strategies for LMS adaptive filtering can fail to converge for cyclostationary signals such as arise in communications. Proposed new partial update strategy which is guaranteed to converge and implemented this algorithm for channel equalization and beamforming.
- Optimal power allocation strategy demonstrated for transmission antennas with smart receive antennas and space time coding under quasi-static flat Rayleigh fading model. First to prove that minimal-distance space-time coding attains computational cut-off rate as number of receive antennas increases.
- Obtained first tractable formulation of channel capacity and channel min-capacity for isotropically random Rician/Rayleigh space time channels. Proved min-capacity for rank one Rician channels is equivalent to capacity for Rayleigh channels.
- First theoretical modeling of a microstrip circuit mounted on 1-D periodic substrate using photonic band-gap concepts
- Improved the performance of conductor-backed half-wave slots by designing a new doubly periodic dielectric substrate
- Developed a new full-wave, integral equation (IE)/periodic moment method (PMoM) code to determine the three-dimensional scattering from singly- and doubly-periodic dielectric layered structures for use in radome/frequency selective surface (FSS) design
- First implementation of higher order Shanks' transforms in the numerical evaluation of the double sum in the 2-D planar periodic free-space Green's function for on-plane elements to improve series acceleration
- Determined scattering from simple dipoles over double periodic dielectric layer over a layered medium
- Emulation of an equivalent uniaxial layer by a doubly periodic dielectric layer
- Validation of the equivalent model for use in planar antenna array applications

## **4 Industrial Interactions and Collaborations**

### **4.1 Raytheon**

We worked with Raytheon on a proposal for the Collaborative Technology Alliance (CTA). The proposed research would have built on the research we have conducted so far under the MURI on low energy wireless communication system design and optimization.

#### **Invited seminars on low power MURI topics**

Besides presenting our research findings at various conferences we have also been invited to present our finding at companies and workshops including: Hughes Network Systems, Lucent Technologies, MIT Lincoln Laboratory, France Telecom, IEEE Communications Theory Workshop, IEEE Systems and Circuits Workshop, Allerton Conference

#### **Students graduating, Place of employment**

- Sangjin Hong: Assistant Professor SUNY (Stony Brook)
- Joesph Kang: Lucent
- Tingfang Ji: Lucent
- Vuk Borich: Applied Wave Research
- Mark Cascito: MIT Lincoln Laboratory
- George Barrett: Johns Hopkins
- J.D. Shumpert: ARF Aperture Systems: Northrup-Gruman
- Chris Lott: Qualcomm
- Paul Liang: Tropian
- Troy Nolan: Harris
- Andrew Worthen: MIT Lincoln Labs
- Do-Sik Yoo: University of Michigan

#### **Industrial Internships**

- Bell Labs, Lucent Technologies (Murray Hill) - Hero (1999)
- Bell Labs, Lucent Technologies (Murray Hill) - Godavarti (2000)
- Rockwell Inc. (LA) - Gupta (2000)